AN ENGINEERING SYSTEM FOR AUTOMATED DESIGN AND OPTIMIZATION OF FUEL CELL POWERED VEHICLES

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ABSTRACT

NREL has contracted Vulcanworks to provide an Advanced Engineering Environment (AEE) configured for development of automotive vehicles powered by fuel cell/fuel processor systems. .

Nuvera Fuel Cells, Inc, provided information for development of relationships and mathematical models of fuel cell and fuel processors.

The Vulcanworks AEE product is an integrated set of tools, tailored to solve design problems in specific environments and processes. The AEE allows extremely rapid iteration of system designs, with automated analysis capability. It contains a database of design and manufacturing rules, an automated geometry creation engine, links to a variety of CAE analysis packages, and a Web-browser interface.

This paper describes a prototype AEE developed for design of vehicles powered by fuel cell/fuel processor systems, including an optimization capability for packaging the propulsion components. It also describes the use of the prototype to assess the following design task:

Optimize the percentage of full power available for the first five minutes of operation from startup

The last section of the paper briefly describes the characteristics of the final design of the AEE, which is planned for developed in further phases of the contract.

PROTOTYPE AEE WORKFLOW

A simplified workflow for the prototype AEE is shown in Figure 1. The user makes several selections in order to initiate a design:

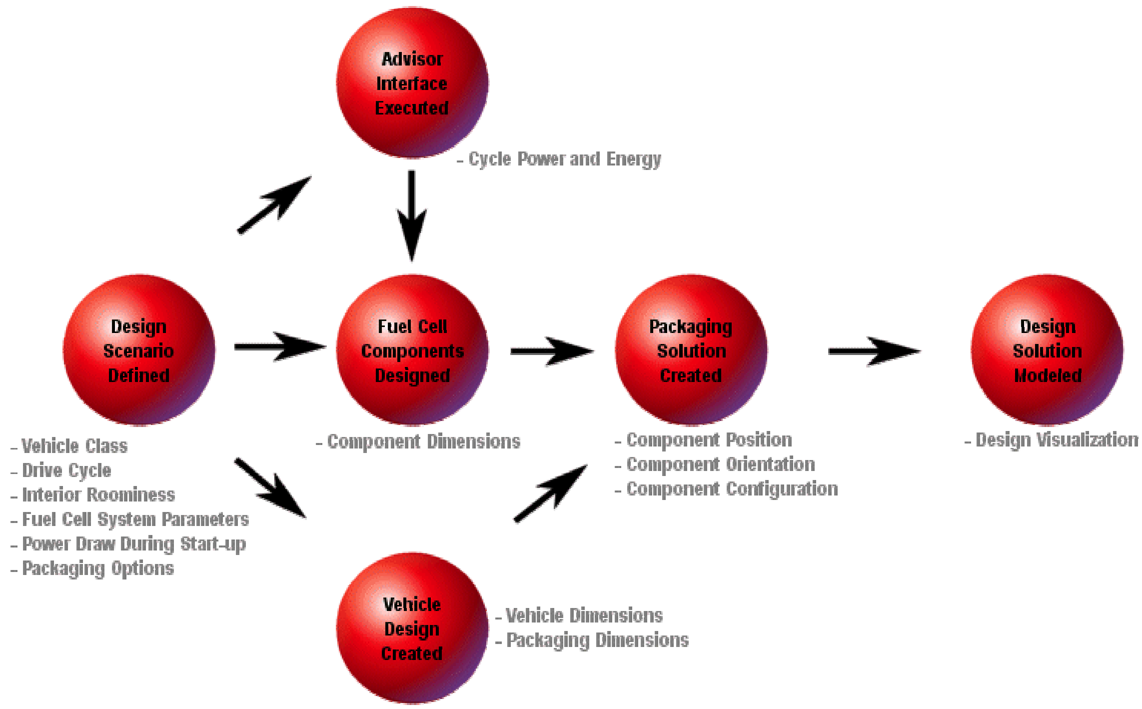
- Vehicle size (class)
- Drive cycle
- Size of the vehicle interior (roominess)
- Fuel cell system operating temperature and pressure
- Packaging options
- Startup conditions

By selecting vehicle class and interior roominess, the user has implicitly limited the amount of volume in the vehicle available for packaging the components of the fuel cell/processor system. The AEE develops models of the vehicle architecture and interior components. It then calculates the resulting volumes available in the front and rear compartments and under the passenger floor. The AEE also estimates the vehicle road load and makes use of a linkage with NREL's ADVISOR program to calculate power demand over the drive cycle.

By selecting operating pressure and temperature, the user has provided the AEE with information it will use to size the components of the propulsion system. From the selected startup conditions, the AEE calculates the time to bring the system to operating temperature, and the supplemental energy, if any, required to power the vehicle during warm-up.

The AEE contains design rules that allow it to utilize these inputs to design all the required components of the vehicle and the propulsion system. Next it uses a proprietary optimization technique to attempt to package the propulsion components into the vehicle. If it cannot, it can selectively increase the vehicle dimensions until a packaging solution is found. At this point, it checks to see whether the initial assumptions it derived for vehicle weight and aerodynamic properties are still valid.

Figure 1: AEE Design Workflow



Elements of the Prototype

In order to execute the design sequence above, the following elements were developed for the prototype AEE:

- 3D parametric models representative of basic 4-door sedan vehicle architecture
- 3D parametric models of fuel cell and fuel reformer system components
- Design alternatives for selected fuel cell system components (alternative aspect ratios for heat exchanges and different allowable shapes for the reformer, steam generator, and fuel cell stack)
- Engineering rules governing vehicle design
- Data sets representing typical C-class (e.g. Volkswagen Jetta) and D-class (e.g. Chevrolet Lumina) architecture derivatives
- Occupant package definition parameters (primarily SAE standards)
- Function versus mechanical design relationships governing fuel cell system component design
- Fuel cell design parameters
- Manual interface to the NREL ADVISOR program.
- Packaging optimizer
- Alternative packaging design sequences

Methods

Vehicle Design

A generic vehicle architecture has been defined for a 4-door sedan. From this architecture, parametric models have been created that are driven from a set of key dimensions to create 3D solid models of major vehicle components. Engineering rules, in turn, calculate these key dimensions based on user selections (in this case, passenger compartment dimensions), thus allowing the creation of a wide variety of alternative derivative vehicles in C and D-classes.

The AEE produces mechanical parameters of a specific design from user selection of the following parameters:

- Vehicle class (C or D)
- Height above ground of the front occupant seating reference point (the hip or "H" point)
- Legroom for the front occupant
- Height above ground of the rear occupant seating reference point
- Distance between front and rear seating reference points on the vehicle's long axis

Based on these selections, engineering rules are invoked that define all major structural and packaging dimensions. Results are visualized by sending these mechanical design parameters to parametric models that are re-formed to produce the requested design. This base design may be redefined to conform to the packaging sequence selected by the user (see below).

Power required

The AEE estimates vehicle weight and aerodynamic drag from the dimensions of the components created to define the vehicle. These values are entered into the NREL ADVISOR program, along with the user-selected drive cycle, and a time history of power required is returned to the AEE.

The AEE determines the maximum power required on the drive cycle, which is used to size the fuel cell components and drive motor. It also retains the power/time history for the first three minutes to be used in startup analysis.

Fuel Cell System Design

Engineering relationships have been derived from a variety of sources (see "References" below) to control the mechanical design of the fuel cell propulsion system components including:

- Fuel reformer and burner (combined) (Doss et al, 1999; Dicks, 1996; Hagan et al, 1998)
- Steam generator and regenerator (combined)
- Fuel cell and saturator (Barbir et al, 1999; Lee et al, 1997)
- System water condenser (Barbir et al, 1999; Doss et al, 2001; Kumar et al, 1998)
- Fuel cell coolant loop heat exchanger (Barbir et al, 1999; Doss et al, 2001; Kumar et al, 1998)
- Air conditioning condenser
- Turbo/compressor
- Batteries
- Traction motor/reduction drive (DeLucchi et al, 2000)

The AEE produces mechanical parameters of the specified design from the maximum required power level and user selection of the fuel cell system operating temperature and pressure. Based on these values, engineering rules are invoked that define all fuel cell component mechanical dimensions. Results are visualized by sending these mechanical design parameters to parametric models that are re-formed to produce the requested design.

Heat exchangers, fuel reformer/burner, and fuel cell/saturator can take a variety of shapes in order to conform to available package space if required. During the packaging operation described below, these alternative shapes will be invoked automatically to try to resolve packaging issues.

Startup Time Analysis

Engineering relationships have been defined that enable the AEE to estimate the "startup time", which is defined as the time from turning the vehicle key on until the fuel cell stack can provide 100% of vehicle power. These relationships compute:

- Time required to raise the fuel cell stack to operating temperature
- Time required to raise the reformer to operating temperature (Doss et al, 1999; Dicks, 1996; Larminie, 2000)
- Reformate CO versus time
- Fuel cell stack CO tolerance (Emonts et al, 1998; Larminie, 2000; Hohlein et al, 1996)

The computation of time required to raise the reformer to operating temperature also makes use of user inputs for:

- Start-up power drawn from turbocompressor
- Whether batteries will be used to power the vehicle during startup
- Amount of time the vehicle is allowed to be stationary before drive-away

Increasing the power drawn from the turbocompressor-driven generator requires more heat to be drawn from the burner, thus reducing the burner heat available to bring the reformer up to operating temperature, and lengthening the time for startup (Barbir et al, 1999; Doss et al, 2001).

Allowing use of batteries improves startup time, but then requires that package room be found for the batteries. In this case, the AEE calculates the required battery energy and power during startup from the power versus time information generated by ADVISOR. The AEE then creates models of the required set of batteries based on rules for power and energy densities for the battery type selected.

Increasing the time the vehicle is allowed to remain stationary reduces startup time and the required volume of batteries, but is a customer-satisfaction detractor that is not favored by vehicle manufacturers.

Component Packaging

The Packaging Optimizer attempts to fit the fuel cell propulsion system components into the packaging space defined by the vehicle architecture and class selection. Compartments are defined for packaging in the front, rear and under-floor areas of the vehicle. Base dimensions of these compartments are defined by the user selection of vehicle design as described above.

Selections are made by the user to control the routines used by the Packager during solution development. These parameters include:

- "Front only" or "Front and Rear" compartment packaging allowed for Power Electronics Module (PEM)
- "Front only" or "Front and Rear" compartment packaging allowed for batteries
- Choice of packaging design sequence

Three packaging design sequences are available to the AEE user:

- Package to available vehicle space - attempt to package the propulsion components but do not increase vehicle dimensions
- Package to fuel cell package requirements – attempt to package the propulsion components; if no solution can be found, increase front compartment width and length progressively by up to 100mm until a solution is found. Also allowed is raising front compartment height up to the cowl height.
- Package with alternative architecture – the user enters a dimension by which the vehicle floor is to be raised (up to 150mm maximum) and the AEE designs a new vehicle with an under-floor compartment. The fuel cell/saturator and fuel reformer/burner may be dynamically sized to maximize usage of under-floor packaging space while maintaining component volumes.

In all three sequences the following process is executed:

- Packaging selections, vehicle design, and fuel cell component designs sent to Packager
- Packaging solution optimized
  - A cost function is provided which is evaluated for each packaging alternative. This cost function can include, for example, the "cost" of the physical separation of two selected components. Such a cost could result from heat losses and therefore efficiency losses as a function of separation distance
  - If required, dynamic heat exchanger dimensional changes can be invoked
- 'Best' packaging solution returned by the Packager based on selected packaging constraints

During execution of the packaging optimization routine, all allowed component orientations and mechanical alternatives are tested for package fit. The Packager attempts to first fit all components into the front compartment. If no solution is found (defined as all components fitted into available packaging space), the Packager attempts to fit all components utilizing other allowed compartments.

Hear Exchanger re-dimensioning is allowed for maximum frontal area usage and front-to-back dimensions as demanded by volume requirements defined to meet system performance.

RESULTS

The AEE System for automated design and optimization of fuel cell powered vehicles provides the capability to execute a wide variety of analyses. Described below are the results of performing a package and design trade-off analysis under a single set of design and operation conditions.

Packaging Alternatives

Several design scenarios were executed using the AEE prototype to demonstrate various design decisions and trade-offs available through use of the AEE.

Table 1 describes the results of each scenario selected. In all cases, the following design selections and assumptions were used:

- Vehicle design is c-class baseline
- Highway drive profile
- Batteries may be packaged in rear compartment
- PEM may not be packaged in rear compartment
- Occupant Packaging
  - Front SGRP (z-axis) 297 mm
  - Rear SGRP (x-axis) 773 mm
  - Rear SGRP (z-axis) 300 mm
  - Effective legroom 815 mm
- Operating Conditions
  - Operating Temp 65 C
  - Operating Press 30 psia
  - Peak Stack Power 50 Kw

Table 1 Packaging results

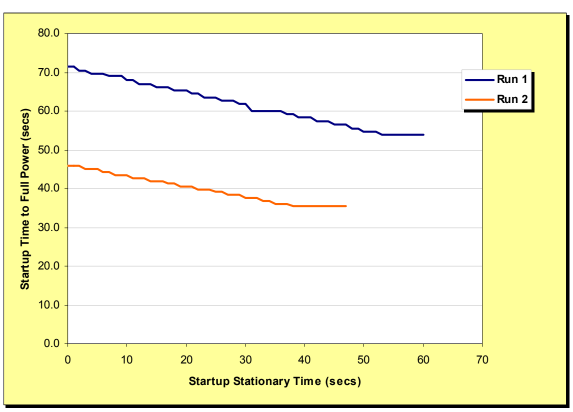
Run Description	Peak Power (Kw)	Cumulative Energy (KwH)	Time to Full Power (secs)	Package Results
Condition 1 • No battery used for start-up • Vehicle stationary to drive-away = time to full power • Start-up power drawn from Turbo = 0 Kw	**0**	**0**	**53.9**	× **Package to Vehicle Dimension** solution not achieved (Turbo not packaged) ✓ **Package to Fuel Cell Dimension** solution achieved ✓ **Package with Under-floor Architecture** solution achieved
Condition 2 • Battery supplements Turbo for start-up • Vehicle stationary to drive-away = 0 • Start-up power drawn from Turbo = 12.5 Kw	**13.505**	**0.111**	**69.7**	× **Package to Vehicle Dimension** solution not achieved (Turbo not packaged) ✓ **Package to Fuel Cell Dimension** solution achieved ✓ **Package with Under-floor Architecture** solution achieved
Condition 3 • Battery used for start-up • Vehicle stationary to drive-away = 0 • Start-up power drawn from Turbo = 0 Kw	**13.505**	**0.092**	**53.9**	× **Package to Vehicle Dimension** solution not achieved (Turbo not packaged) ✓ **Package to Fuel Cell Dimension** solution achieved ✓ **Package with Under-floor Architecture** solution achieved

Stationary Startup Time

Fuel cell operating conditions for this analysis were defined for each run as described in Table 2 below. Start-up power supplied from batteries was 0Kw.

Stationary time at start-up was varied from 0 to total start-up time and the effect on time to full power was captured.

Table 2 Startup results



CONCLUSIONS

1. The prototype AEE has successfully demonstrated the ability to perform the design task
2. The results of tradeoff studies using the AEE provide useful information to fuel cell/reformer system designers
3. The relationships that determine fuel cell/reformer component size and startup performance are adequate to create credible designs. These relationships can be readily updated for a particular fuel cell/reformer system as equations and data become available (e.g. from a proprietary design).
4. The prototype demonstrates all the important functions of the final design and has therefore validated the design of the final AEE system. The prototype design is robust enough to evolve into the final design without rework

PROPOSED FURTHER DEVELOPMENT

The contract included the design of the complete AEE for fuel cell powered vehicles. Although description of the design is outside the scope of this paper, below is a brief description of its expected capabilities:

- Design tradeoffs in the fuel cell and fuel processor
- Integration with systems to develop vehicle package alternatives, structure, and suspension designs
- Integration of analyses to predict performance of the vehicle, such as energy efficiency analysis, performance analysis (gradeability, acceleration, load capacity, top speed, range), vehicle accessory capacity analysis (air-conditioning, heated backlight, etc.), and stability and cornering capability analysis

- Prediction of structural performance
- Optimization capability spanning all of the above in order to develop optimal designs for various vehicle mission assumptions
- Development and evaluation of alternative designs for fuel cells/fuel processors and vehicles with design output for each alternative including 3D solid model geometry and system performance prediction
- The final design has built on the success of the prototype and is therefore of very low risk
- This design provides significant functionality for:
  - Designing advanced propulsion systems such as fuel cell/reformer systems
  - Evaluating the vehicle implications of fuel cell/reformer system design and operation
  - Evaluating the impact at the vehicle and vehicle fleet levels of proposed targets for vehicles powered by advanced propulsion systems
- The design is highly flexible for accommodating advanced technology, by readily allowing addition and enhancement of:
  - Design rules and relationships
  - Linkages to external analysis packages
  - Models of alternative component designs
  - Models of alternative system designs.

REFERENCES

Barbir, Balasubramanian, Neutzler, 1999, Trade-off Design Analysis of Operating Pressure and Temperature in PEM Fuel Cell Systems, AES-Vol. 39, ASME

DeLucchi, Burke, Lipman, Miller, 2000, Electric and Gasoline Vehicle Lifecycle Cost and Energy-Use Model, UC Davis

Dicks, 1996, Hydrogen generation from natural gas for the fuel cell systems of tomorrow, *Journal of Power Sources* 61 pp. 113-124

Doss, Ahluwalia, Kumar, 1999, Pressurized and Atmospheric Pressure Gasoline-Fueled Polymer Electrolyte Fuel Cell System Performance, SAE 1999-01-2574

Doss, Kumar, Ahluwalia, Krumpelt, 2001, Fuel processors for automotive fuel cell systems: a parametric analysis, *Journal of Power Sources* 102 pp. 1-15

Emonts, Hansen, Jorgensen, Hohlein, Peters, 1998, Compact methanol reformer test for fuel-cell powered light-duty vehicles, *Journal of Power Sources* 71 pp. 288-293

Hagan, Northrop, Bowers, Rumsey, Prabhu, 1998, Automotive Fuel Processing Systems for PEM Fuel Cells, SAE

Hohlein, Boe, Bogild-Hansen, Brockerhoff, Colsman, Emonts, Menzer, Riedel, 1996, Hydrogen from methanol for fuel cells in mobile systems: development of a compact reformer, *Journal of Power Sources* 61 pp. 143-147

Kumar, Ahluwalia, Doss, Geyer, Krumpelt, 1998, Design, Integration, and Trade-Off Analyses of Gasoline-Fueled Polymer Electrolyte Fuel Cell Systems for Transportation, 1998 Fuel Cell Seminar, Palm Springs, California

Larminie, Dicks, 2000, *Fuel Cell Systems Explained*, Wiley

Lee, Lalk, Appleby, 1998, Modeling electrochemical performance in large scale proton exchange membrane fuel cell stacks, *Journal of Power Sources* 70 pp. 258-268